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LETTER TO THE EDITOR

HIP 114328: a new refractory-poor and Li-poor solar twin^{★,★★}

Jorge Meléndez¹, Lucas Schirbel¹, TalaWanda R. Monroe¹, David Yong², Iván Ramírez³, and Martin Asplund²

¹ Departamento de Astronomia do IAG/USP, Universidade de São Paulo, rua do Matão 1226, Cidade Universitária, 05508-900 São Paulo, SP, Brazil
 e-mail: jorge.melendez@iag.usp.br

² Research School of Astronomy and Astrophysics, The Australian National University, Cotter Road, Weston ACT 2611, Australia

³ McDonald Observatory and Department of Astronomy, University of Texas at Austin, USA

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ABSTRACT

Context. The standard solar model fails to predict the very low lithium abundance in the Sun, which is much lower than the proto-solar nebula (as measured in meteorites). This Li problem has been debated for decades, and it has been ascribed either to planet formation or to secular stellar depletion due to additional mixing below the convection zone, either during the pre-main sequence and thus possibly linked to planet formation, or additionally on secular time-scales during the main sequence. In order to test the evolution of Li, it is important to find solar twins in a range of ages, i.e., stars with about one solar mass and metallicity but in different evolutionary stages. Furthermore, the study of stars similar to the Sun is relevant in relation to the signature of terrestrial planet formation around the Sun, and for anchoring photometric and spectroscopic stellar parameter scales.

Aims. We aim to identify and analyse solar twins using high quality spectra, in order to study Li depletion in the Sun and the possible relation between chemical abundance anomalies and planet formation.

Methods. We acquired high-resolution ($R \sim 110\,000$), high S/N (~ 300) ESO/VLT UVES spectra of several solar twin candidates and the Sun (as reflected from the asteroid Juno). Among the solar twin candidates we identify HIP 114328 as a solar twin and perform a differential line-by-line abundance analysis of this star relative to the Sun.

Results. HIP 114328 has stellar parameters $T_{\text{eff}} = 5785 \pm 10$ K, $\log g = 4.38 \pm 0.03$, $[\text{Fe}/\text{H}] = -0.022 \pm 0.009$, and a microturbulent velocity 0.05 ± 0.03 km s⁻¹ higher than solar. The differential analysis shows that this star is chemically very similar to the Sun. The refractory elements seem slightly more depleted than in the Sun, meaning that HIP 114328 may be as likely to form terrestrial planets as the Sun. HIP 114328 is about 2 Gyr older than the Sun, and is thus the second oldest solar twin analysed at high precision. It has a Li abundance of $A(\text{Li})_{\text{NLTE}} \lesssim 0.46$, which is about 4 times lower than in the Sun ($A(\text{Li})_{\text{NLTE}} = 1.07$ dex), but close to the oldest solar twin known, HIP 102152.

Conclusions. Based on the lower abundances of refractory elements when compared to other solar twins, HIP 114328 seems an excellent candidate to host rocky planets. The low Li abundance of this star is consistent with its old age and fits very well the emerging Li-age relation among solar twins of different ages.

Key words. Sun: abundances – stars: fundamental parameters – stars: abundances – planetary systems

1. Introduction

Since we can observe the Sun only at its current age, we have to rely on younger and older stars to understand how the Sun would have been or how it will be at different evolutionary stages. The ideal sample of stars to compare the Sun with are solar twins (Cayrel de Strobel 1996). Although solar twins are usually defined based on the similarity of their spectra to the Sun (e.g., Datson et al. 2014) or stellar parameters (e.g., Ramírez et al. 2009), here we refer to solar twins as main-sequence stars with about one solar mass and about solar composition, but spanning a range of ages. Having a mass and composition similar to the Sun ensures that solar twins will follow about the same evolutionary path as the Sun, thus allowing us to study the evolution of the Sun in time. As the stellar parameter space covered by main-sequence stars of one solar mass and roughly solar metallicity ($[\text{Fe}/\text{H}] = 0.0 \pm 0.1$ dex) is broader than the working

definition of solar twins given by Ramírez et al. (2009), which is T_{eff} within 100 K, $\log g$ within 0.1 dex, and $[\text{Fe}/\text{H}]$ within 0.1 dex of the solar values, all previous solar twins are included in our definition.

Of particular importance is the study of lithium; this element has been potentially related either to planet formation (Israelian et al. 2004, 2009; Chen & Zhao 2006; Gonzalez et al. 2010; Takeda et al. 2010; Delgado Mena et al. 2014; Gonzalez 2014) or to stellar depletion as stars evolve (Meléndez et al. 2010; Baumann et al. 2010; Monroe et al. 2013). A sample of solar twins with a range of ages is crucial to better understand this element, which can be used as an important constraint for non-standard stellar evolution models (Charbonnel & Talon 2005; Xiong & Deng 2009; do Nascimento et al. 2009; Baraffe & Chabrier 2010; Denissenkov 2010; Li et al. 2012).

Several bright ($V < 10$) solar twins have been identified already (Porto de Mello & da Silva 1997; Meléndez et al. 2006, 2009; Meléndez & Ramírez 2007; Takeda et al. 2007; Takeda & Tajitsu 2009; Ramírez et al. 2009; Datson et al. 2012, 2014; Porto de Mello et al. 2014), so they can be subject to high signal-to-noise ratio (S/N), high resolving power ($R = \lambda/\delta\lambda$)

[★] Based on observations obtained at the European Southern Observatory (ESO) Very Large Telescope (VLT) at Paranal Observatory, Chile (observing program 083.D-0871).

^{★★} Table 1 is available in electronic form at <http://www.aanda.org>

studies, i.e., to high precision analyses using a high figure of merit $F = (R[S/N])/\lambda$ (Norris et al. 2001). For example, the work by Ramírez et al. (2011) achieved a precision of about 0.01–0.02 dex in chemical abundances using $F \sim 4000$, while both Meléndez et al. (2012) and Monroe et al. (2013) achieved a precision of about 0.005–0.010 dex with $F \sim 10\,000$, and Meléndez et al. (2014) achieved a precision of about 0.005 dex with $F \sim 15\,000$. Among those solar twins studied at high precision ($F \gtrsim 4000$), only 16 Cyg B (Ramírez et al. 2011) and HIP 102152 (Monroe et al. 2013) seem older than the Sun.

In this Letter, we report the identification of another solar twin older than the Sun, HIP 114328 (HD 218544), thus bringing important insights on the evolution of Li and therefore on the mechanisms that destroy this fragile element in solar-type stars. We will also discuss the refractory-poor abundance pattern of this star in the context of chemical anomalies and planet formation.

2. Observations

Based on their colors and Hipparcos parallaxes, we selected eight solar twin candidates for spectroscopic observations, HIP 1536, HIP 3238, HIP 10725, HIP 11514, HIP 106288, HIP 109381, HIP 114328, and HIP 117499, as well as the asteroid Juno to obtain a reference solar spectrum. The observations were taken using UVES in dichroic mode, with the 346 nm setting (306–387 nm) in the blue arm and the 580 nm setting (480–682 nm) in the red arm.

Most of the spectral lines that we used are in the red arm, where we achieved $R = 110\,000$ using the 0.3 arcsec slit. The typical S/N is about 285 per pixel, thus our figure of merit is $F \sim 5000$. In the UV we used a slit of 0.6 arcsec, resulting in $R = 65\,000$.

The spectral orders were extracted and wavelength calibrated using IRAF. Further data processing was performed with IDL. A comparison of the solar twin candidates to the Sun, revealed that only the spectrum of HIP 114328 accurately matched the solar spectrum, hence this star was selected for a further detailed analysis. Part of the reduced spectra of HIP 114328 and the Sun is shown in Fig. 1 in the region 6078–6095 Å and around the Li feature. The spectra are very similar, except for the Li feature, with HIP 114328 showing a much weaker feature than the Sun, and similar to the old solar twin HIP 102152 (Monroe et al. 2013).

3. Abundance analysis

The analysis is similar to that presented in Meléndez et al. (2012, 2014) and Monroe et al. (2013). The main difference is that here all equivalent width (EW) measurements were performed by hand, instead of first having a set of automatic measurements with ARES (Sousa et al. 2007). The number of outliers in the manual measurements is significantly smaller than those obtained in our previous works when using EWs measured automatically. Thus, we needed to check the manual measurements only for a few lines. The line list is from Meléndez et al. (2014), and is an extended version of that presented in Meléndez et al. (2012).

The same differential approach as in our previous papers was used to obtain stellar parameters and chemical abundances, i.e., we followed a strictly differential line-by-line analysis. We adopted ATLAS9 model atmospheres (Castelli & Kurucz 2004), although the differential analysis of solar twins is essentially insensitive to the chosen grid of model atmospheres

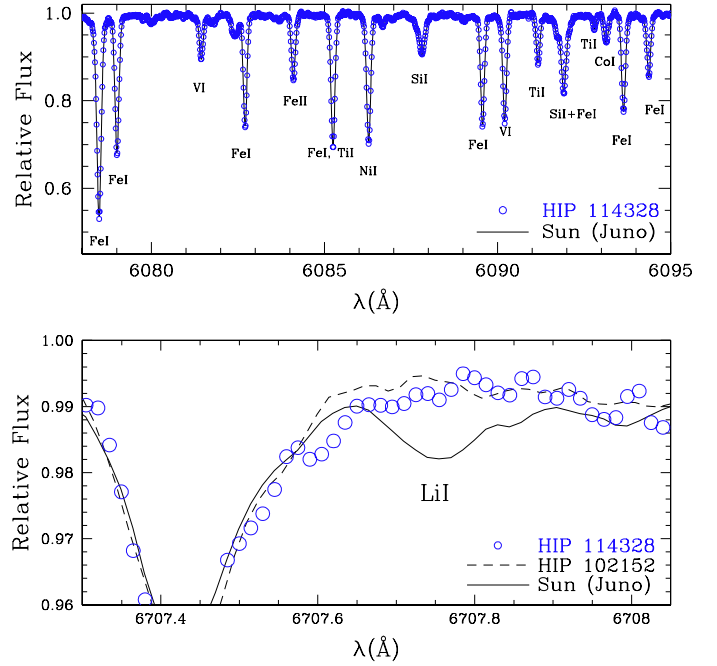


Fig. 1. Comparison of the spectra of HIP 114328 (blue circles) and the Sun (solid line) around 609 nm (*top panel*), showing that both stars have similar spectra. The Li feature for HIP 114328, HIP 102152, and the Sun, is shown in the *bottom panel*. HIP 114328 has a Li feature substantially weaker than solar and comparable to the old solar twin HIP 102152.

(Meléndez et al. 2012). The analysis was performed using the 2002 version of the local thermodynamic equilibrium (LTE) code MOOG (Sneden 1973). As shown in Meléndez et al. (2012, 2014) and Monroe et al. (2013), differential non-LTE corrections in solar twins are negligible, hence they are not taken into account here.

The differential spectroscopic equilibrium of HIP 114328 relative to the Sun results in stellar parameters of $T_{\text{eff}} = 5785 \pm 10$ K ($\Delta T_{\text{eff}} = +8 \pm 10$ K), $\log g = 4.38 \pm 0.03$ dex ($\Delta \log g = -0.06 \pm 0.03$ dex), $[\text{Fe}/\text{H}] = -0.022 \pm 0.009$ dex, and a microturbulent velocity $+0.05 \pm 0.03$ km s⁻¹ higher than solar. The errors in the stellar parameters were estimated based on the observational uncertainties and take into account the degeneracy in the stellar parameters.

Once the stellar parameters were set, we computed differential abundances using the measured EWs, except for Li, which was analysed by spectrum synthesis using the line list of Meléndez et al. (2012). Hyperfine structure was taken into account for V, Mn, Co, and Cu. The differential abundances are provided in Table 1, as well as the observational errors (standard errors), the errors due to uncertainties in the stellar parameters, and the total error, obtained by adding in quadrature the observational and systematic errors.

In Fig. 2 we plot the differential abundances $[X/\text{H}]$ between HIP 114328 and the Sun (circles) as a function of equilibrium condensation temperature (T_{cond} , Lodders 2003). The abundance pattern of HIP 114328 is similar to solar and seems slightly more depleted in refractories than the Sun, as shown by the fits (solid and dashed lines). Considering the uncertainties, the refractory-to-volatile ratio in HIP 114328 is similar to solar. For comparison, the mean abundance pattern of eleven solar twins (Meléndez et al. 2009), is shown by a dot-dashed line, showing that HIP 114328 is indeed depleted in refractories.

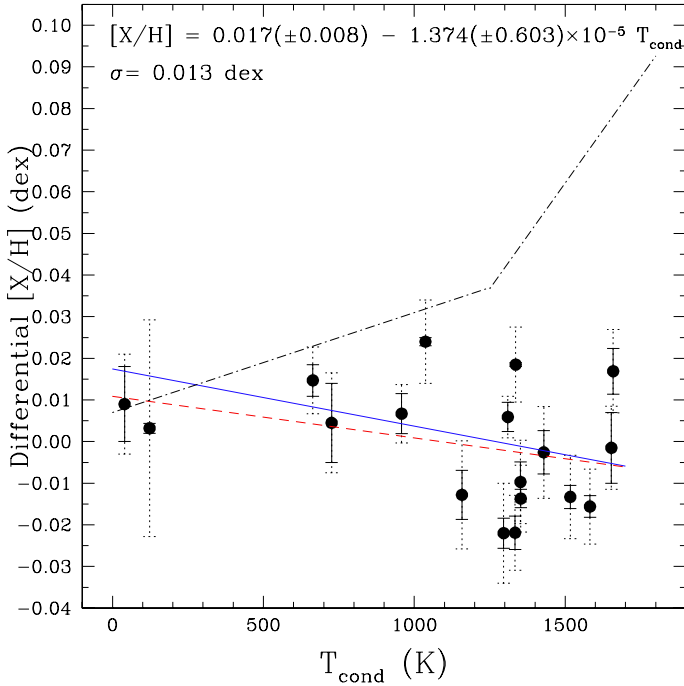


Fig. 2. Abundance pattern of HIP 114328 (circles) vs. condensation temperature. The solid error bars are based only on the observational uncertainties, and the dotted error bars are the total errors (average ~ 0.011 dex). The solid line is a fit taking into account the total error bars and the dashed line is a fit without considering error bars. The element-to-element scatter from the fit is only $\sigma = 0.013$ dex, in good agreement with the mean error bar. The dot-dashed line is the mean abundance pattern of 11 solar twins from Meléndez et al. (2009), shifted vertically to match the volatile element carbon.

The element-to-element scatter (0.013 dex) of the differential abundances in HIP 114328 is similar to the typical error bar of the differential abundances (0.011 dex), showing that our error bars are realistic and that we achieved a typical error of ~ 0.01 dex.

The LTE lithium abundance in HIP 114328 is $A(\text{Li}) \lesssim 0.41 \pm 0.13$, and the NLTE abundance is $A(\text{Li})_{\text{NLTE}} \lesssim 0.46 \pm 0.13$, using the NLTE corrections of Lind et al. (2009). This low Li abundance is slightly higher than the Li abundance in the old solar twin HIP 102152 (Monroe et al. 2013), and as discussed below, reinforces the idea of secular stellar depletion.

4. Discussion

There are not many studies of HIP 114328 in the literature, only two papers are reported by SIMBAD, one on stellar activity (Jenkins et al. 2011) and the other one on a list of candidates for targeted transit searches (Herrero et al. 2012). There are three earlier papers on delta Scuti stars, but they are actually misidentifications, and refer to DY Peg (HD 218549) and not to HIP 114328 (HD 218544).

The abundance pattern of HIP 114328 is very similar to solar (Fig. 2) and seems even slightly more depleted in refractories than the Sun. The abundance pattern of the Sun is different from most solar twins (Meléndez et al. 2009; Ramírez et al. 2009), probably due to the formation of the terrestrial planets in the solar system (Chambers 2010). Thus, the chemical similarity between HIP 114328 and the Sun, may suggest that HIP 114328 was as well equipped as the Sun to host rocky planets.

An alternative hypothesis to explain the Sun’s abundance anomalies is that the viewing angle of solar twins from Earth is different than the angle of the Sun when observed from Earth. However, a detailed analysis of solar spectra taken at different solar latitudes revealed no abundance differences (Kiselman et al. 2011). Another explanation put forward by Önehag et al. (2011), is that the lack of refractory elements may actually reflect that the star was born in a dense environment as suggested by the analysis of one solar twin in the open cluster M67. Interestingly, the recent work by Adibekyan et al. (2014), shows that older stars have a lower refractory-to-volatile ratio than younger stars, thus suggesting that age may play a role in the trends with condensation temperature. However, the recent discovery of clear abundance differences between the binary components of 16 Cygni (Laws & Gonzalez 2001; Ramírez et al. 2011; Tucci Maia et al. 2014), where the secondary hosts a giant planet but no planet has been detected around the primary despite more than two decades of radial velocity monitoring, strongly suggests that planet formation can indeed imprint chemical signatures on the composition of their host stars. We note that although both Schuler et al. (2011) and Takeda (2005) found no abundance difference between 16 Cyg A and B, their work is based on spectra with a lower figure of merit (i.e., lower quality) than in Tucci Maia et al. (2014), who used a resolving power $R = 81\,000$ and $S/N = 700$, implying $F = 9450$ at 6000 \AA . On the other hand, Schuler et al. (2011) used $R = 45\,000$ and $S/N = 750$, hence their $F = 5625$. The work of Takeda (2005), made use of $R = 70\,000$ spectra, which had a low $S/N = 90\text{--}130$ (Takeda et al. 2005), resulting in a much lower figure of merit ($F = 1280$).

Using our precise stellar parameters with their error bars, Yonsei-Yale isochrones (Kim et al. 2002; Demarque et al. 2004) and probability distribution functions (as described in Meléndez et al. 2012), we estimate an age and mass for HIP 114328 of $6.7^{+0.6}_{-1.1}$ Gyr and $0.99 \pm 0.01 M_{\odot}$, respectively. The old age of this solar twin is consistent with the low activity level measured by Jenkins et al. (2011), $R_{\text{HK}} = -5.024$, fitting well the activity-age relation of solar twins (Ramírez et al. 2014).

We plot the Li abundance and age of HIP 114328 in Fig. 3, together with the solar twins used by Monroe et al. (2013), which are all based on analyses with high figure of merit ($F \geq 4000$) and $R \geq 60\,000$. In this plot we updated the age of 16 Cyg B (previously from Ramírez et al. 2011) using the most precise stellar parameters of Tucci-Maia et al. (2014), resulting in an age of $6.6^{+0.3}_{-0.4}$ Gyr. We also plot several theoretical tracks of non-standard models of lithium depletion (Charbonnel & Talon 2005; do Nascimento et al. 2009; Xiong & Deng 2009; Denissenkov 2010). HIP 114328 fits well the Li-age correlation found by Monroe et al. (2013). This connection between Li and age has already been suggested, albeit with larger uncertainties, in our earlier works (Meléndez et al. 2010; Baumann et al. 2010). This reinforces that stellar Li depletion is secular and not related to planet formation (e.g., Israelian et al. 2009); the low Li content in the Sun is perfectly normal for its age. Overall there is a good agreement with all non-standard models shown in Fig. 3.

5. Conclusions

We achieve a precision of about 0.01 dex in the differential analysis of HIP 114328 relative to the Sun. This solar twin has a chemical composition similar to solar, hence it is a good place to look for potential rocky planets. First identifying a Sun 2.0, or solar twin, with potential terrestrial planet formation, such as HIP 114328, is perhaps a good strategy for researchers to

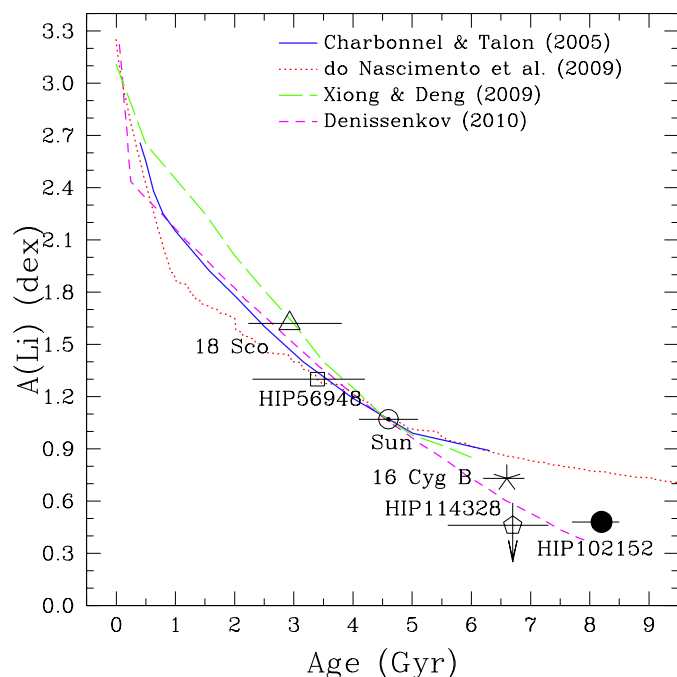


Fig. 3. NLTE Li abundances vs. age for the Sun and solar twins observed at high spectral resolution and high S/N. The total error bar ($\pm\sigma$) of the Li abundance is about the size of the symbols, while the error bars in age are shown by horizontal lines. For comparison we show the models by Charbonnel & Talon (2005); do Nascimento et al. (2009); Xiong & Deng (2009); and Denissenkov (2010), shifted to reproduce our observed NLTE solar Li abundance. The model with initial rotation velocity of 50 km s⁻¹ was adopted from Charbonnel & Talon (2005). HIP 114328 is shown by a pentagon, and helps to define a clear Li–age correlation.

consider as they search for an Earth 2.0, or Earth-sized planet in the habitable zone of a sun-like star. Although originally not included in our HARPS planet survey around solar twins (Ramírez et al. 2014, ESO Large Program 188.C-0265, PI: J. Meléndez), we will start to search for planets around this star.

We determine an old age for HIP 114328 (~7 Gyr), which makes it important to study the depletion of Li with age. The low Li abundance of HIP 114328 fits very well an emerging tight relation between Li and age, and shows that Li could be used as a cosmo-chronometer, thus helping to derive ages in main-sequence stars (do Nascimento et al. 2009; Li et al. 2012). The study of more solar twins in a range of ages will help to better constrain non-standard stellar evolution models.

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Table 1. Differential abundances of HIP 114328 relative to the Sun and errors.

Element	LTE	ΔT_{eff} +10 K	$\Delta \log g$ +0.03 dex	Δv_t +0.03 km s ⁻¹	$\Delta[\text{Fe}/\text{H}]$ +0.01 dex	Param ^a	Obs ^b	Total ^c
	(dex)	(dex)	(dex)	(dex)	(dex)	(dex)	(dex)	(dex)
C	0.009	-0.005	0.007	0.000	-0.001	0.009	0.009	0.012
N	0.003	0.013	0.007	0.020	0.009	0.026	0.001	0.026
Na	0.007	0.005	-0.001	0.000	0.001	0.005	0.005	0.007
Mg	0.019	0.005	-0.006	-0.004	0.000	0.009	0.001	0.009
Al	-0.002	0.005	-0.001	-0.001	0.001	0.005	0.009	0.010
Si	0.006	0.002	0.001	-0.001	0.001	0.003	0.004	0.005
S	0.015	-0.004	0.006	0.000	0.000	0.007	0.004	0.008
Ca	-0.013	0.007	-0.005	-0.005	0.001	0.010	0.003	0.010
Sc	0.017	0.008	0.002	-0.001	0.001	0.008	0.006	0.010
Ti	-0.016	0.004	0.005	-0.005	-0.002	0.008	0.003	0.009
V	-0.003	0.010	0.001	-0.002	0.001	0.010	0.005	0.011
Cr	-0.022	-0.002	0.010	-0.004	0.002	0.011	0.004	0.012
Mn	-0.013	0.008	-0.004	-0.007	0.002	0.012	0.006	0.013
Fe	-0.022	0.001	0.005	-0.006	0.002	0.008	0.004	0.009
Co	-0.010	0.008	0.003	-0.002	0.001	0.009	0.005	0.010
Ni	-0.014	0.006	0.000	-0.005	0.002	0.008	0.002	0.008
Cu	0.024	0.006	-0.001	-0.007	0.003	0.010	0.001	0.010
Zn	0.005	0.001	0.002	-0.006	0.003	0.007	0.010	0.012

Notes. Abundances of V, Mn, Co, and Cu account for HFS. ^(a) Adding errors in stellar parameters. ^(b) Observational errors. ^(c) Total errors (stellar parameters and observational).